P4 Astro/Cosmo/Particle Physics Working Group Summary Statement

Snowmass, CO, July 2001

The goal of this working group was to identify opportunities for advances in particle physics with astrophysics and cosmology. The activities of this working group have shown that, since the previous Snowmass meeting in 1996, there have been spectacular advances in cosmology and particle astrophysics. These include, but are not limited to, cosmic microwave background (CMB) evidence for inflation, supernova and CMB evidence for negative-pressure dark energy, and results from solar and atmospheric neutrino experiments. Taken together, these results demonstrate that astro/cosmo/particle physics is an integral component of the particle physics research enterprise.

The P4 Working Group covered a very broad range of topics, subdivided into eight topical groups:

1. Dark Matter
2. Gamma-rays and X-rays
3. Cosmic Microwave Background and Inflation
4. Large Scale Structure and Cosmological Parameters
5. Cosmic Rays
6. Gravitational Radiation
7. Neutrinos
8. Early Universe and Tests of Fundamental Physics

There is intense experimental and theoretical activity in all of these areas. Every major breakthrough listed below has been made since the previous Snowmass, and the prospects for the next decade and beyond are even brighter. It is not possible to describe here all the work discussed during the past three weeks. Instead, we emphasize the over-arching themes that these areas represent and their great relevance to the purpose of Snowmass 2001.

- In cosmology, there have been spectacular observational breakthroughs:
    - Recent CMB measurements provide evidence that the total energy density of the universe, Ω, is close to 1. For the first time, we may know the geometry of the Universe.
    - Observations support the hypothesis that large-scale structure grew from primordial density fluctuations, in agreement with predictions from inflation. This provides the scientific connection between the large-scale structure of the Universe and elementary particle physics, and is indicative of new physics at higher energy scales.
    - The discrepancy between $\Omega_{matter} \sim 0.3$ and $\Omega \sim 1$ provides independent corroboration of the remarkable recent supernova survey evidence for some form of 'dark energy'. If confirmed, this suggests that ~70% of the energy density of the Universe is of a previously unknown and mysterious

  type. The existence of the dark energy was not even suspected by most physicists at the time of the previous Snowmass.
  - The CMB data cannot be explained without the existence of non-baryonic dark matter, implying physics beyond the Standard Model. This strengthens the case for some form of particle dark matter (e.g., super-symmetric particles or axions) in our Galactic halo.

- At the same time that the theoretical case for non-baryonic dark matter continues to strengthen, the prospects for advancing the measurements over the next decade, with both direct and indirect detection methods, are fantastic. A fleet of experiments with complementary sensitivities and systematics are probing deeper into theoretically well-motivated regimes of particle physics parameter space.
- Underground observations of solar neutrinos and cosmic ray-induced atmospheric neutrinos, indicating the existence of neutrino oscillations, have provided evidence that neutrinos are not massless. This is the first direct experimental confirmation that the Standard Model is incomplete.
- The most massive black holes are central to TeV-class astrophysical accelerator systems that have been observed to radiate immense power in gamma rays. Unprecedented leaps in sensitivity will be made by the next-generation of both ground-based and space-based gamma-ray instruments, opening up large discovery spaces. Together, these gamma-ray measurements also provide a unique probe of the era of galaxy formation, and will provide the first significant information about the high-energy behavior of gamma-ray bursts.
- The evidence for the highest energy cosmic ray events ($E>10^{20}$ eV) poses significant challenges to our theoretical understanding. Observations underway, and new detectors under construction and in planning, both on the ground and in space, will shed the first light on this highest-energy mystery. These experiments, as well as high-energy neutrino telescopes, will allow us to exploit the highest-energy particles for particle physics.
- Soon, the Universe will be viewed not only with photons, but also with high-energy charged particles, high-energy neutrinos, and gravity waves. These observations will test strong-field general relativity and open vast new windows on the highest-energy astrophysical phenomena and the early Universe.

Interest in astro/cosmo/particle physics has grown remarkably since the previous Snowmass meeting.   Of the five "P" groups at Snowmass 2001, the subscription to P4 (217 people as of 14 June) was second only to that of P1, Electroweak Symmetry Breaking, and the overlap with all of HEP was obvious in P4 joint sessions with other groups. Interest in the Snowmass-wide teach-in on astro/cosmo/particle physics was very strong.

In summary, there is vigorous and fast-growing activity in astro/cosmo/particle physics, and the intellectual overlap between our community and others – especially the high-energy astrophysics and cosmology communities – has grown into full and healthy partnerships, greatly accelerating progress. These partnerships provide enormous opportunities and some challenges.